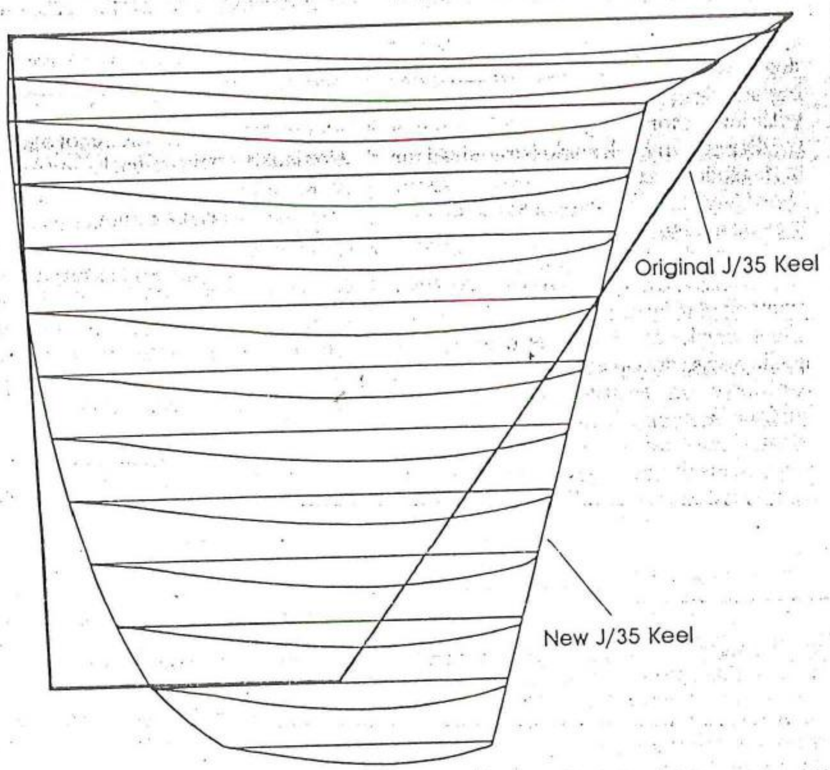
A WINNING KEEL



David Vacanti explains the innovative keel he designed for the SORC-winning J/35 *My Fair Lady*, and makes a case for a long keel root chord.

As a developer of yacht design and analysis software, I have long awaited a chance to comment on what I consider to be an incorrect keel design technique – the current practice of using a very short keel root chord length on fin keels. (For those of you who don't deal often with "foil" lingo, the "keel root chord" is the section of the keel closest to the hull. For definitions of this and other terms, please see the glossary.)

Typically, a short root chord is combined with an "elliptical" keel shape, which allows the use of longer chord lengths lower, near the middle of the keel draft.

The logic of the current elliptical keel design methodology appears hard to argue with, because the short root chord is intended to reduce the keel/hull interference drag (see glossary), and the longer chord lengths near the middle of the keel span can hold large volumes of lead, thereby significantly lowering the vertical center of gravity of the keel. The lower center of gravity means improved stability, and increased speed. The only obvious design problem is the thin root section, which makes attaching the keel to the hull very difficult. Using the "elliptical" planform shape to achieve a lower center of gravity is a good concept, but I don't believe it is necessary to incur the difficult mechanical problems of a very small root chord to reduce drag.

My chance to prove that the small root chord is an unnecessary evil came when I was asked to design a new keel for the J/35 *My Fair Lady*. The new keel was part of an overall plan to make her more competitive in the 1988 SORC IMS class. In order to understand how the design of this J/35 keel evolved, let's first examine the problems I believe are inherent with the current elliptical keels.

Besides the obvious attachment problems the short root chord creates, there are two main areas where performance may suffer: 1. reduction of the end-plate effect (see glossary) of the keel against the hull; 2. the placement of the longer chord lengths near mid-draft of the keel causes the center of effort to move towards the tip of the keel, especially when the elliptical shape is combined with a large leading-edge sweep-back angle.

Now let's explore these concepts i

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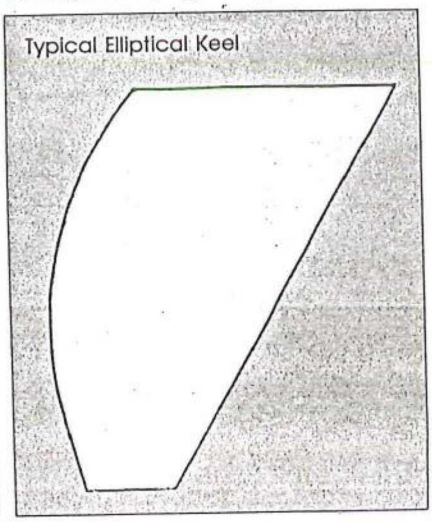
more detail. In order to understand my first point about a reduction in end-plate effect, let's take an extreme case where we shorten the root chord until it no longer attaches to the hull, and we have some magical way to carry this keel along under the hull as we sail. As we shorten the root chord, we diminish the end-plate effect to the point where the keel is removed from the hull, and we have an open end generating additional vortex drag and reduced lift. Now, instead of having only the keel tip open and generating vortex drag (remember that wings were added to *Australia II*'s keel to reduce vortex drag), the open root chord is also creating vortex drag. When the keel is attached to the hull, more lift is generated because there is only one open end of the keel for the water flow to escape around. However, there is some undesirable interference drag at the keel/hull joint.

My second concern with the current elliptical keel designs and their short root chords is with the keel's center of effort. If you have sailed an unballasted racing dinghy with a centerboard, you are keenly aware that heel angle can be considerably reduced when sailing upwind in heavy air by pulling up the centerboard part way. A sailboat literally trips herself on her keel when resisting the sideforces of the sails when hard on the wind. This occurs because the keel side force or lift acts at a center of effort location below the center of buoyancy, opposite to the direction of the sail forces, which act through the sails' center of effort located high above the center of buoyancy. The result is a large rolling moment to leeward. Moving the keel area such that it concentrates lifting forces farther down the keel span, like that shown in elliptical keels, tends to lower the keel center of effort and is detrimental to stability and performance.

Another factor that exacerbates the design problems of the short root chord is the sweep angle of the leading edge. Towing tank drag tests, conducted at Delft in the Netherlands, showed that sweeping back a keel's leading edge 45 degrees or more is beneficial in reducing the drag of a low-aspect ratio keel with long chord lengths, while a much smaller sweep-back angle is required for high-aspect ratio keels with shorter chord lengths.[1] These experimental findings are also supported by research work done for the keel of *Stars & Stripes '87*, which stated in summary, "The primary planform parameter which can affect the level of viscous drag is the leading-edge sweep angle. Large sweeps can have an adverse effect on the laminar boundary layer... Optimization of foil shape and planform geometry for low viscous drag can produce an efficient keel capable of overall sailing performance gains."[2] In 1985 I published a reference work on keel performance parameters using computer analysis, and showed clearly that large sweep-back angles on high-aspect ratio keels are detrimental to performance.[3]


Typical Elliptical Keel

It is important to note that significant amounts of drag are generated by keels with large sweep-back angles (greater than 25 degrees). Minimum vortex drag for any given keel sweep angle is achieved by selecting the proper taper ratio. (See Taper Ratio graph.) However, the taper ratios for large sweep angles require an extremely short keel tip that approaches a point, while smaller sweep-back angles allow longer keel tip lengths. Since the extreme taper ratio required of large sweep-back angles is never achieved in practice, these keels exhibit high levels of vortex drag. Even if the proper taper ratio is achieved in highly swept keels, the minimum vortex drag levels of these keels is always higher than that of a minimally swept keel.

Not only does a large sweep-back angle cripple the performance of high-aspect ratios keels; it also helps move the keel center of effort still lower on the keel span by encouraging water to flow down the span of the keel instead of along the desired root-chord direction. Obviously, sweep-back angle simply compounds the problem of reduced stability described above.

While the mathematics and scientific papers are impressive, there is nothing more convincing than a winning record in a major sailing event. The SORC-winning keels carried by *Abracadabra* in 1986 and *Sprint* in 1987 sported longish root chords, 15-degree sweep-back angles, and a special high cross-section NASA foil shape after they were optimized by Bernard Nivelt with my analysis software.

At this point we can summarize a formula for low performance by specifying an elliptical keel planform, com-

Glossary

Chord: All lengths measured from the leading edge to the trailing edge of a keel, rudder or wing are referred to as chord lengths or chords.

Root Chord: The end of a keel or rudder that attaches to the hull is referred to as the "root" end. When we refer to the length of this end, we call it a "root chord."

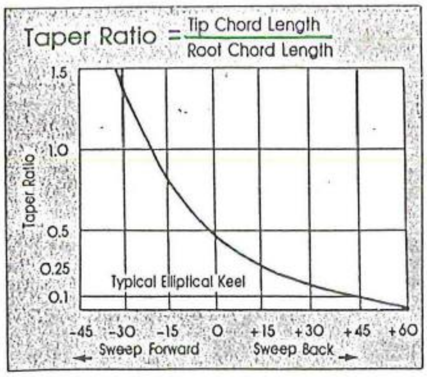
Planform: The shape of the keel when it is viewed from abeam of the hull, allowing the viewer to see the leading and trailing edge shapes

Span: The height of the keel, measured from the root to the tip

Vortex: When the forward motion of the boat is combined with the natural escape of water from the high-pressure (leeward) side to the low-pressure (windward) side at the keel tip, the water leaving the tip is forced to spin. The spinning motion is called a vortex, much like the swirl of water seen in a bathtub drain. The spinning waterflow represents energy that was dissipated by the keel without generating lift. Any time we expend energy without developing useful work, like lift, we account for it as drag–in this case vortex drag.

End-Plate Effect: Even the Wright Brothers understood that if an open wingtip could be sealed with an "end plate" such as a flat piece of light metal, they could prevent the natural escape of air from the wing bottom to the top side, and thus prevent a loss of lift and generated drag. The hull of a boat always acts as an end plate at the upper end of the keel; the best known case of creating an end plate at the tip is the use of winglets on 12-Meters and shoal-draft cruising keels. It's a means to force the water flow to remain over the keel surface and prevent its escape around an open tip.

Interference Drag: Drag occurs whenever the energy present in a fluid flow is dissipated in some wasted form without creating lift. Whenever two objects of different sizes or orientations are placed in close proximity to one another, the fluid flow between them must adopt a speed and direction approximately the average of the two independent flows. This cannot be done without the slower flow speeding up (absorbing energy) and the faster flow slowing down (giving up energy). The result of this flow interference and adjustment is energy loss that does not result in lift.



The points on this curve define the taper ratio needed for minimum drag for a given sweep-back angle. A typical elliptical keel swept back 45 degrees requires a tip chord one tenth as long as the root chord to achieve minimum drag – practically impossible to achieve.

bined with a short root chord and a sweep-back angle of more than 30 degrees. This design technique significantly lowers the keel center of effort, and negates the lowered center of gravity obtained when the longer chords are placed at mid-span, thereby reducing stability and sail drive. The large sweep-back angle produces higher vortex drag due to reduced keel efficiency, increases viscous (friction) drag, and produces less keel sideforce per unit of keel area. If the designer is not careful in minimizing his choice of mid-span chord lengths, the aspect ratio may also be reduced, further degrading potential keel performance.

Having dealt the elliptical keel myth what I think is a considerable blow, where can we turn for a design solution to the problems of reducing keel/hull interference drag, while improving stability and keel efficiency? Our criticism of the short root-chord design contains the answers. If we assemble a list of desired characteristics, we can create a design approach. We need a good seal of the keel to the hull, and we need a relatively long chord to allow sufficient area to place keel bolts. We need a small leading-edge sweep angle for the keel, but we also have a conflicting need to sweep back the long root chords to reduce interference drag. We also need to lower the center of gravity to help improve stability.

Here's the design approach:

A: Rather than shortening chord lengths to reduce interference drag, a more pragmatic approach is to use a relatively large radius fillet along the keel as it joins the hull. This makes the different flow speeds and directions along the hull/keel joint occur more gradually. It is also advisable to use a fairing at the keel leading edge where it joins the hull, to help make the transition more gradual in this region as well. These techniques are very common in aircraft design.

B: Based on the Delft towing tank test results, we can use a large sweep-back angle only in the vicinity of the long root chord to reduce interference drag. The long root chord will provide the necessary area to achieve high mechanical strength.

C: Use a small leading-edge sweep angle below the root-chord area, chosen to match the taper ratio of the keel to achieve minimum vortex drag, and maximum keel efficiency.

D: Use a laminar flow (low drag), high cross-section area foil shape to hold more lead without long chord lengths. This foil shape reduces drag and can be used to lower the center of gravity without moving the center of effort. The center of effort will not shift because the required lead volume can be achieved with a shorter chord length, thus avoiding the need for long chord lengths at mid span.

E: Make the upper keel section an empty sump, allowing room for a reasonable bilge and keeping lead low in the remaining keel span.

So far I have mentioned two concepts that need more explanation. The first idea is using a large sweep-back angle near the hull to reduce interference drag, and the second is the need for a special foil shape.

An excellent example of using sweep angle to reduce interference drag is found on the advanced X-29 fighter currently under development. The X-29 uses highly swept-forward wings for remarkable maneuverability, because the forward sweep causes the inboard end of the wing to stall first in tight turns, thus maintaining lift over the wing tips and the critical aileron control surfaces (see drawing). However, the swept-forward design causes inboard spanwise flow which piles up at the wing/fuselage junction, thereby increasing interference drag. This problem was solved by inserting a short wing section near the fuselage which is swept *aft*, before the remaining wing span is swept forward. The aft-swept section next to the airframe directs the inboard flow away from the fuselage, thereby reducing the interference drag.

A positive fallout of this design is a beneficial vortex that forms at the leading-edge joint in the wing between the different sweep angles. This vortex becomes an active "fence" that limits the outward (down in a keel) flow, and adds energy into the local flow to help maintain laminar (low drag) conditions.

A foil shape recently designed by NASA for low-speed general aviation aircraft provides a large cross-sectional area, laminar flow characteristics, resistance to stall, and high-lift coefficients. The foil was originally called the GA-W for General Aviation-Whitcomb, after Richard Whitcomb, the father of the winglet at NASA. The foil series has since become known simply as the LS or Low Speed series. As originally designed, this foil shape was cambered and concave in the after sections. I have modified the foil shape using a foil analysis program to allow its use as a symmetric foil in keel design. The foil shape has a large radius nose section that allows it to achieve high angles of attack and resist stall. It is also capable of generating what is known as leading-edge suction, which in effect is a force in the direction of travel. This concept is exactly analagous to the forward driving force created by a sail all along its highly-cambered leading edge.

These design factors were combined

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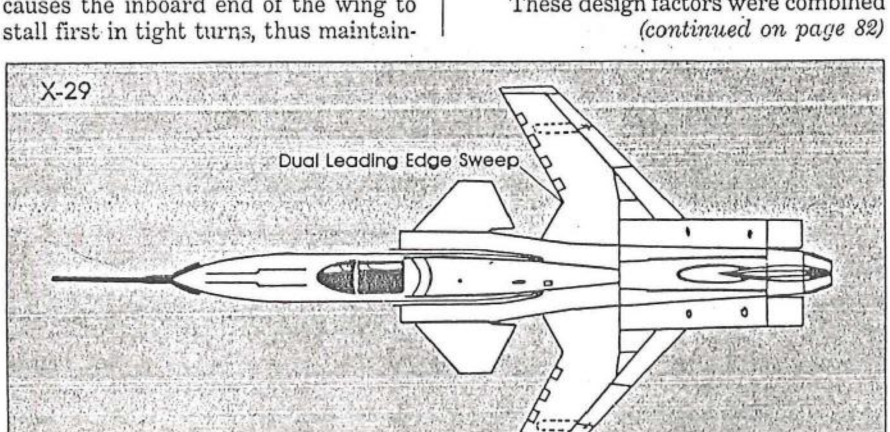

The dual leading-edge wing-sweep on the new X-29 fighter minimizes interference drag at the wing/fuselage junction. The author took a similar approach with his new J/35 keel by using a large sweep-back angle at the root chord and then a very small sweep-back angle for the rest of the keel.

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into the keel that played a role in winning the 1988 SORC for the J/35 *My Fair Lady*. Several people who saw the keel before it raced in the SORC were concerned about the long root chord, and about the "kink" in the leading edge. The concept of double leading-edge angles or "cranked" wings has been used extensively, as shown in the case of the X-29. It is possible, however, to overdo the cranked wing concept and generate a low-performance, non-linear lift-vs.-leeway characteristic.

Research work conducted by the Dutch hydrodynamicist Joop Sloof indicated that it was desirable to reduce the amount of lift generated by the keel near the root chord.[4] This was to be accomplished by reducing the chord lengths near the root chord and increasing them near the keel tip. Mr. Sloof indicates that this inverted keel planform with a longer tip chord than root chord requires a swept-forward leading edge for optimum performance. It is important to note that by shortening the root-chord lengths the intent is to reduce the strength of the keel wake near the water surface. This is important because the keel wake near the surface generates wave drag. However, the inverted taper ratio is only beneficial at hull speed and has diminishing value at lower speeds. Mr. Sloof's research makes no mention of how to offset the effects of lowering the center of effort, and the increased heeling moment that will result—and of course the same mechanical problems of the short root chord will occur. His arguments for reducing wave drag are valid, but I'm concerned that some designers are using a short root chord without following through on his entire concept.

The final concern many sailors may have is the problem of catching kelp with a nearly vertical section when using minimal sweep angles. My only response to this concern is that I have seen many highly swept-back keels do a more than adequate job of kelp harvesting, and when they were not farming, their self-limiting performance was robbing their owners of well-deserved first-place honors. •

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1. "Experimental Analysis of Five Keel/Hull Combinations," J. Gerritsma and J.A. Keuning. The Seventh Chesapeake Sailing Yacht Symposium, 1985.
2. "Keel Design for Low Viscous Drag," Clifford J. Obara and C.P. van Dam. The Eighth Chesapeake Sailing Yacht Symposium 1987.
3. "Keel Parameters and Performance," David C. Vacanti, *SAIL* magazine, August 1985.
4. "On Wings and Keels II," J.W. Sloof. Ancient Interface XV, AIAA Symposium on the Aero-Hydrodynamics of Sailing Vol. 31, September 1985.